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Hemp-Lime Performance in Danish Climatic Context. Thermal Conductivity as a Function of Moisture Content.

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Abstract

In order to fit low energy building policies and reduce environmental impact of buildings, construction materials must have good balance between thermal properties and embodied energy. By using such materials, reduction of both operational and embodied energy are achieved simultaneously.

Hemp concrete is a bio-based building material composed of the woody core of industrial hemp and lime based binder. It is a non-load-bearing material, which can be used as floor and around structural frames for walls and roof. The material is characterized by relatively low environmental impact, moderate thermal properties and, high air and moisture permeability. The properties vary with binder composition, mixing and casting techniques, as well as intended application.

This research presents preliminary heat and moisture building simulations of single family house made out of hemp-lime composite. To evaluate the performance of hemp-lime, it is compared to models with common external walls, upon defined parameters.

The article also determines the variation of thermal conductivity for hemp-lime commercial plaster and wall mix, as a function of moisture content. The most promising binder composition and mixing proportions for the wall mixture are identified through literature review; thereafter samples for the experiment are prepared and tested in laboratory environment. Thermal conductivity is found by using Hot Plate Apparatus λ-meter EP500, while moisture dependence is established upon testing samples with different moisture content.

Results from the experiments show non-linear increase in thermal conductivity with increase in moisture content. The results and potential benefits of using hemp-lime are discussed and conclusions are drawn.

Keywords – hemcrete; HAM simulations; energy performance;

1. Introduction

Buildings impact the environment by consumption of resources and emission of greenhouse gasses (GHG). Development of sustainable buildings can substantially reduce the extraction of natural materials, minimize GHG emissions and total energy consumption [1]. In order for a building to be sustainable, it must be with small environmental footprint over its life-cycle, energy efficient, with healthy indoor environment, etc.

Use of bio-based building materials can be a solution to the aspect of embodied energy. Such materials can be attained from renewable biological resources, such as wood [2], earth [3], straw [4], coconut [5], hemp [6] etc.

Hemp is a multipurpose plant, which can be used in construction for insulation [7], mortar and filling composites [8, 9]. Generally insulation materials are produced from the fibbers of the plant, while mixture of the hemp shiv and lime based binder provides composites, suitable for monolithic construction.

Using Hemp-lime (HL) as construction material benefits the environment in several ways. Firstly, hemp is a fast growing plant, which prevents growth of weeds and does not require pesticides. It is known as good rotational plant, because its short roots help aerate and replenish the soil. When mixed with lime binder, the hemp composite absorbs carbon dioxide, which is caused by the curing of the lime. Life cycle assessments of HL composites are performed by [10, 11]. Both studies conclude that hemp concretes have negative carbon footprint, as the uptake by photosynthesis and carbonization is greater than the emissions associated with the ready material.

The use of hemp in combination with lime based binder is well known and researched in countries such as France [12], United Kingdom [13], Sweden [14], Italy [15], etc. Despite that, it is not well known in Denmark so far. Therefore, the aim of this paper is to asses HL performance in Danish weather conditions by comparing it to common construction materials. HL performance is assessed by performing and comparing heat and moisture simulations of a low energy, single-family house made of HL and common construction materials. As the amount of low-energy homes built in the future is expected to grow, all simulation models are made in a way that require less than 20 kWh/m^2 annually for heating.

HL is known to have relatively low densities varying from 200 to 600 kg/m^3[6], which results in lower thermal conductivity when comparing to common monolithic construction materials. HL is also characterized by high ability to uptake and release moisture (Moisture Buffer Value) [12,16,17]. Because of thi the thermal conductivity varies with varying moisture content.

To determine the value of the thermal conductivity for building simulations with HL and its variation with moisture content, experimental procedure for two HL mixes is established.

2. Methods

A. Heat and Moisture Simulations

The aim of the simulations is to examine if HL is comparable with commonly used construction materials under Danish climate conditions. The simulations are performed with the dynamic building simulation software tool BSim. The computer program calculates and analyses indoor climate conditions, energy consumption and power demand of buildings by detailed mathematical models. Design Reference Year (DRY 2013) is used for all simulated models.

BSim model of a single family house, described in [18], is used as a basis for obtaining three additional simulation models with different wall and roof types. They can be seen in Table 1. Each construction is modelled in a way that the U-value of the envelope is kept constant. This is done with the aim to examine how moisture content in the construction affects the heating need and thermal comfort.

Table 1 Specification of investigated construction types.

Main Material	External walls			Roof		
	Constr. type	Thickness [mm]	U-Value [W/(m^2·K)]	Constr. type	Thickness [mm]	U-Value [W/(m^2·K)]
Wood	Sapwood Stone wool Sap wood	16 468 16	0.08	Sapwood Stone wool Sapwood	16 468 16	0.08
Hemp	HL Plaster HL Wall HL Plaster	25 650 25	0.08	HL Plaster HL Wall HL plaster	25 650 25	0.08
Brick	Brick Stone wool Brick	108 450 108	0.08	Sapwood Stone wool Sapwood	16 468 16	0.08
Concrete	Concrete Stone wool Concrete	150 470 50	0.08	Sapwood Stone wool Sapwood	16 468 16	0.08

HL is proven to have good or excellent moisture buffer value [12,16,17], in accordance with the Nordtest Poject classification [19]. For that reason, an interest of the simulations presented in this paper, is to investigate the influence of HL on indoor air relative humidity (RH). This is evaluated by comparison of the following parameters for each construction type: annual indoor air RH distributions and hourly values for one month in the heating season. All performed analysis focus on zone 1 (bedrooms and office in the model), as it is subjected to periodic moisture loads.

BSim is able to predict moisture transport trough materials based on defined absorption, desorption and vapor permeability curves. Therefore, considerable effort has been made to obtain representative curves for the different materials. The models presented in this paper use interpreted data, obtained by [20] for HL and [21] for brick. Moisture transport responsible parameters for wood and concrete are taken from the BSim database.

Majority of building materials experience some moisture variation, and thus thermal conductivity variation. For materials with poor moisture buffer values, the overall effect of the thermal conductivity variation with moisture content is likely to be insignificant. However, for materials which have high moisture buffer capacity, such variation might be larger in magnitude and present for longer period of time throughout the year. In such case, modeling thermal conductivity as a function of moisture content would provide more realistic results.

Relation of thermal conductivity with moisture content is currently not an option in BSim. To check if it should be modelled, the variation of moisture in the construction, obtained by the simulations, is compared to results from the performed experiments (Figure 4).

The systems integrated in the models are kept as described by [18]. Each model includes temperature-controlled ventilation and venting, as well as scheduled equipment, infiltration, moisture and people loads.

B. Measurments

Thermal conductivity measurements at different moisture content of the specimens are obtained by applying the following procedure for two HL mixes; specified in section 3.

The specimens are tested at four moisture contents throughout their drying cycle. The exact moisture content for each tested specimen is determined by its dry weight. Dry weight is achieved by oven drying in accordance with [22]. It requires consecutive weightings of specimens in a period of minimum 24 hours while drying. Dry weight is reached when the change in mass of the specimen, between three consecutive measurements, is less than 0.1% of the total mass.

Thermal conductivity is determined by use of Hot Plate Apparatus λ-meter EP500. To prevent moisture escaping during the experiments, each specimen is wrapped in vapor impermeable foil, where special care is taken to eliminate air pockets between the HL specimen and the foil. In order to ensure full contact between the specimens' top and bottom sides and the heating plates of the apparatus, additional thin layer of ultrasound gel is added on both sides of the specimen. The gel is enclosed by another plastic foil, thereafter the specimen is placed in the apparatus for testing.

Steady state experiment is performed for each specimen. The apparatus seeks to have predefined, constant temperatures, at the specimens' boundaries by adjusting the applied flux. Thermal conductivity is given when it changes less than 1.5% over 60 minutes. Derivation can be then obtained by formula (1).

$$Q = \lambda/d \cdot \delta T \tag{1}$$

Where

Q	Heat flux	[W/m^2]
λ	Thermal conductivity	[W/(m·K)]
d	Thickness	[m]
δT	Temperature difference	[K]

Thermal conductivity is derived explicitly as the apparatus knows the applied heat flux, thickness of the sample and temperature difference.

3. Materials

A. *Wall mixture*

The shives used for the wall mixture are of Belgium origin, produced for construction purposes with small amount of fibers. Table 2 presents binder ratios and hemp to binder ratios by mass, used in studied mixtures by different authors, see references in Table 2. As seen from the table, the main materials used in HL binders are hydrated and hydraulic lime, pozzolanic additive fly ash and cement. Cement is used in order to speed up the drying process, which allows for quicker removal of scaffolding on site. Cement also lowers vapor permeability and thus the ability of the final material to regulate indoor RH [6]. Faster curing can be considered a short-term benefit, as this is related mainly to duration of construction works. Reduction of vapor permeability, however, is a long term disadvantage, as this property would be lower throughout the life cycle of the material. Addition of cement would also result in a higher embodied energy of the material which is unwanted. Therefore cement is not used in the mix, prepared for the current experiments.

Based on data presented in Table 2, the following binder composition by mass for wall mixture is chosen: 0.75 hydrated lime, 0,15 hydraulic lime, 0.1 Fly ash. Hemp to binder ratio is chosen as 0.5, while water to binder ratio is set to 3 and adjusted accordingly in order to achieve a mix passing “snow ball” test.

Table 2 Binder and composition ratios of hemp-lime concretes

Reference	Binder ratio by mass				Ratio by mass	
	Hydrated lime	Hydraulic lime	Fly ash	Cement	Hemp/Binder	Water/Binder
[8]	**0.75**	**0.15**	**0.1**	**-**	**0.5**	**-**
[23]	0.76	0.15	0.09	-	0.56	2,05
	0.75	0.15	0.10	-	0.88	2.44
[24]	0.70	0.20	0.10	-	0.50	3.10
[25]	0.25	0.75	-	-	0.28	1.06
	0.40	0.60	-	0.33	-	1.33
	0.29	0.44	-	0.27	0.30	1.20
	0.20	0.30	-	0.50	0.28	1.11
	-	-	-	1.00	0.22	0.89
[26]	0.44	0.33	-	0.22	0.95	2.62

Hemp shives and binder are initially mixed in pan mixer, thereafter water is added to the mix. This mixing procedure reduces water demand and shortens drying time, without compromising long term properties [24].

Four wall specimens were used for the experiments. Their average dry density is found to be 136.30 ± 3.22 kg/m^3.

B. Commercial binder

Commercially available specimens, made by the company “Hemp Eco Systems”, are the second studied mixture in this paper. The mix consists of hemp shives with French origin, hydrated lime "Lhoist – FAXE Hydratkalk", HES-plus additives and water. Due to competitiveness with the remaining commercial companies on the market, the contents of the HES-plus mix cannot be provided by the company. The producer classifies the mix as more suitable for plaster applications; therefore its thermal conductivity is used for the inner and outer plater layer of the simulated HL construction, specified in Table 1. The samples were poured at the company’s premises in previously prepared molds. Thereafter, transported to the laboratory and taken out of the molds. In total 3 specimens with densities of 316.08 ±11.74 kg/m^3, were used for the experiments.

4. Results

A. Simulation Results

Energy use for heating for all four studied cases is presented in Figure 1. The results show that, the lowest energy use for heating, due to material moisture content, is in the case with concrete. This result may not be realistic as concrete is found to have limited moisture buffering value by [19]. Additionally comparisons of the hygric properties of the studied materials revealed that concrete’s sorption and desorption curves have the largest magnitude of all.

HL construction requires the second lowest heating demand of 14,08 kWh/m^2 annually, followed by brick with 14.28 kWh/m^2 annually, and wood with 15.72 kWh/m^2 annually. From Figure 1 it is apparent that, HL slightly lowers heating need compared to bricks and approximately 10% lower, compared to wood.

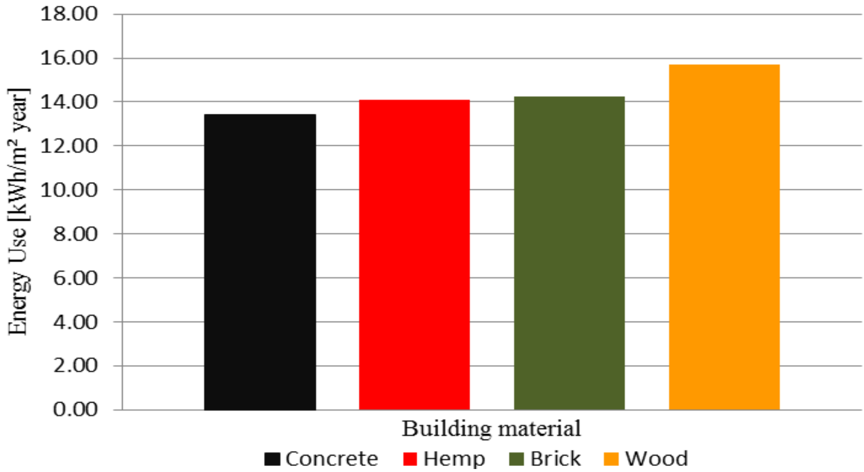

Figure 1 Energy use for heating

Indoor air RH distribution for the studied cases is shown on Figure 2. Distributions for wood and concrete are identical, while distribution for brick is the closest to that of HL. The results suggest that HL reduces the amount of hours in the range of 25 - 40% indoor air RH. It is interesting to note that for the higher range of RH (50 - 65%), HL seems to have the lowest amount of hours associated with each data point.

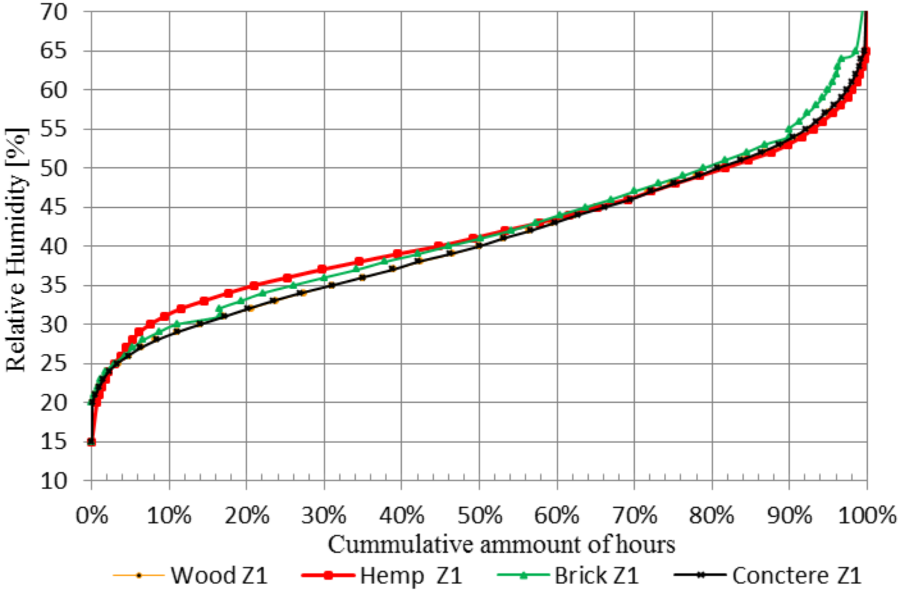

Figure 2 Cumulative indoor air relative humidity distribution in zone 1.

The results presented in Figure 2 are further evaluated upon design criteria for indoor air RH category classification in accordance with [27]. Category range and amount of time that each model fulfills the category requirements are presented in Table 3. The greatest difference is noticed for category I, where HL fulfills the requirements for 4.2% more hours compared to wood and brick, and 7.5% more hours compared to concrete.

Table 3 Amount of hours each studied material fulfills indoor environment classification in accordance with [27].

Category	Range	% of hours in a year			
	Relatve Hummidity [%]	Hemp	Wood	Brick	Concrete
I	>30 | <50	74.2 %	66.9 %	70.0 %	66.7 %
II	>25 | <60	95.2 %	94.5 %	94,9 %	94.1 %
III	>20 | <70	99.3 %	99.9 %	100 %	99.9 %
IV	<20 | >70	0.7 %	0.1 %	0.0 %	0.1%

Hourly variations of indoor air RH, throughout January, are presented in Figure 3. It is apparent that HL has the highest levels of indoor RH, while brick construction provides slightly lower values than HL. The cases with concrete and wood have nearly identical values throughout the presented period and are with the lowest RH levels of all.

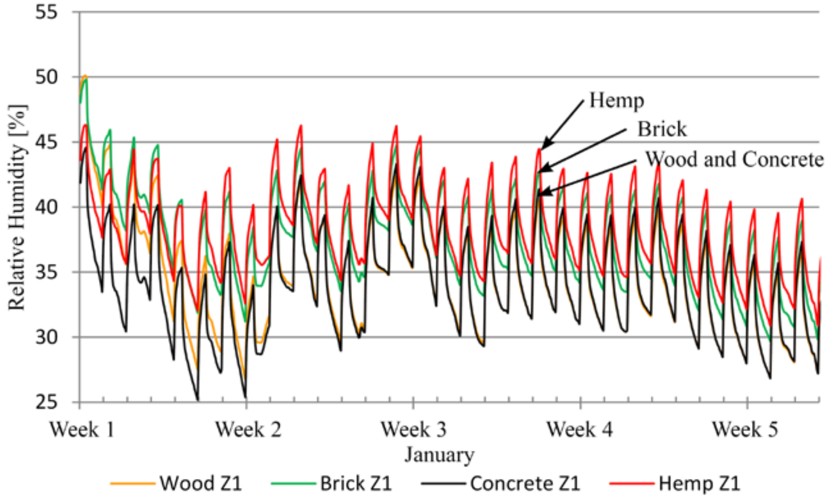

Figure 3 Hourly values of indoor air relatie humidity occuring in January.

B. Thermal condictivity as a function of moisture content

Figure 4 presents the results for thermal conductivity as a function of moisture content for both studied materials. The results show that thermal conductivity for both mixtures increase with moisture content. Values for moisture dependency are given in the range of 0 – 84% and 0 – 18% moisture content by mass for wall and commercial mix, respectfully.

The variation of moisture content in the construction, found by simulations, is within the range of 3 – 10 % moisture content by mass (represented by the dotted lines in Figure 4).

As noted in section 3, the density of the commercial specimens, varies by 11,74 kg/m^3. This large variation resulted in higher thermal conductivity at 10% moisture content by mass. This was accounted for by comparison of the thermal conductivity at dry state of all specimens. The data point was then normalized by the average difference of thermal conductivity between the commercial specimens at dry state.

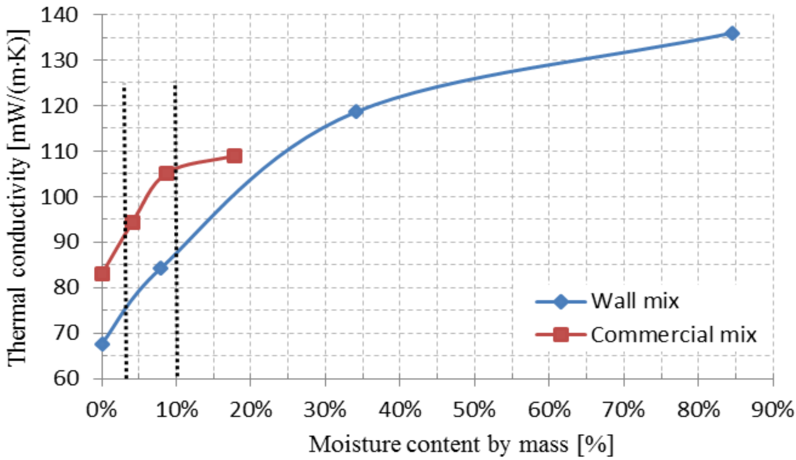

Figure 4 Thermal conductivity measurments as a function of moiture content by mass.

5. Discussion

Results from the initial simulations presented in Figure 1 show that all studied construction types have nearly the same energy required for heating. The lowest of all is for the case with concrete, which is believed to be partly due to overestimated sorption and desorption curves and partly to the high thermal mass of concrete. Furthermore, analysis of the indoor air RH levels show, that when HL is used, values in the low range of RH (25-35%), occur for 5% less hours during a year. As RH in households is typically lowest during the heating season, it is reasonable to argue that this refers to higher RH during the heating season. This is further observed by the analysis presented in Figure 2 and Table 3.

The measured data for thermal conductivity for wall specimens is given in the range of 0-84% moisture content by mass, whereas for commercial mix the results are for the range of 0-18%. That is due to the fact that the specimens representing common wall mix were prepared in laboratory conditions and tested shortly after they were removed from the molds. The case with commercial mix specimens, the first test was performed nearly one month after the materials were casted. The variation of thermal conductivity throughout the year, based on results obtained by the simulations, suggests that thermal conductivity would vary with about 17% for both wall and commercial mixture. Therefore modeling thermal conductivity as a function of moisture content for HL buildings could provide more accurate building simulation results.

6. Conclusion

The paper presents initial simulation of single family house build from HL and compares it to three commonly used construction materials. The results show that HL is comparable to common materials under Danish weather conditions. Simulation' results indicate that HL might slightly damp daily variations of indoor air RH and reduce the number of hours occurring in the low range of 25-35% indoor air RH. Close correlation between hemp and brick was noticed for both energy use and indoor RH in Figure 1 and Figure 2, respectively.

In order to evaluate the relation of thermal conductivity with moisture content, commonly used binder mix was established and tested alongside with commercially available mix. The thermal conductivity increases with increase in moisture content for both materials. Slightly higher increase is noticed for the commercially available mixture than for the wall mixture. Comparison between material moisture content variations and moisture depended thermal conductivity is presented in Figure 4. Results show thermal conductivity would variate by 17%, which might have too large of an effect to be disregard in building simulations.

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